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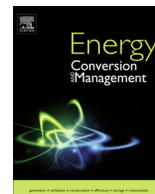
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# Hybrid wind–photovoltaic–diesel–battery system sizing tool development using empirical approach, life-cycle cost and performance analysis: A case study in Scotland



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## ABSTRACT

The concept of off-grid hybrid wind energy system is financially attractive and more reliable than stand-alone power systems since it is based on more than one electricity generation source. One of the most expensive components in a stand-alone wind-power system is the energy storage system as very often it is oversized to increase system autonomy. In this work, we consider a hybrid system which consists of wind turbines, photovoltaic panels, diesel generator and battery storage. One of the main challenges experienced by project managers is the sizing of components for different sites. This challenge is due to the variability of the renewable energy resource and the load demand for different sites. This paper introduces a sizing model that has been developed and implemented as a graphical user interface, which predicts the optimum configuration of a hybrid system. In particular, this paper focuses on seeking the optimal size of the batteries and the diesel generator usage. Both of these components are seen to be trade-offs from each other. The model simulates real time operation of the hybrid system, using the annual measured hourly wind speed and solar irradiation. The benefit of using time series approach is that it reflects a more realistic situation; here, the peaks and troughs of the renewable energy resource are a central part of the sizing model. Finally, load sensitivity and hybrid system performance analysis are demonstrated.

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## 1. Introduction

Lack of affordable and reliable electricity supply is a major impediment to the development of many rural communities, particularly those remote from the existing electricity grid. This is especially true in developing countries, where off-grid systems are often the only practical solution for electricity generation. Traditionally, off-grid systems rely solely on diesel generators, but a significant rise in oil prices has made diesel-based systems uneconomic. Recent developments in renewable generation technologies allows the use of natural resources (wind, hydro, or photovoltaic (PV)) as alternative energy sources, but their intermittency typically results in inadequate energy supply for a substantial proportion of the year. However, combining renewable energy sources (RES) with conventional diesel generation and energy storage systems in so called “hybrid renewable energy systems” may provide reliable electricity supply with reduced battery storage and/or diesel requirements. A fossil fuel-based generation is suggested to be

incorporated into the system rather than solely increasing the wind turbine or PV sizes excessively to cope with the worst month [1]. Moreover, the utilisation of two or more RES is economically beneficial especially for locations whereby weather changes significantly across seasonal variations [2]. In addition, it has been studied that due to the high initial cost of the system, government subsidy is necessary to adopt the system on a large scale basis in the remote areas [3]. Even though the cost of electricity generated from most of the hybrid energy systems are higher than that of the national grid electricity tariff, the cost of national grid extension to these remote areas are difficult and uneconomical [4].

Several literatures have studied the sizing of hybrid energy systems. Earlier work [5] simply shows the generation capacity is determined to best match the power demand by minimising the difference between total power generation and load demand over a period of 24 h. The author iteratively optimised the components by using hourly average data of wind speed and solar irradiation in meeting a specific load demand. In [6], the authors further utilised linear programming technique to optimise the sizing of the hybrid system components (battery capacity and diesel fuel usage) within the 24 h period. Kaldellis et al. [7] pointed out that focusing on the

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installation cost is insufficient for a hybrid system sizing methodology which is based on simplified cost analysis. Operation and maintenance (O&M) costs take up a large proportion of the overall cost of the system over its lifetime. Thus, Kaldellis has developed a method to calculate long-term energy-production cost for a wind-diesel hybrid system by taking into consideration fixed and variable costs of maintenance, operation and financing, and initial costs. Alternatively, the authors in [8] have developed an algorithm to optimally size a standalone hybrid wind-diesel system by considering the total system reactive power balance condition. In another mean of selecting the optimal combination of a hybrid renewable energy system to meet the demand, evaluation was conducted on the basis of reliability of the system by considering the loss of load probability (LOLP) [9]. The LOLP sensitivity analysis on total installation cost has been demonstrated in [10] for the considered hybrid system. In a different perspective, the authors in [11] described an optimal energy storage sizing method by considering the compensation cost of wind power and load curtailment.

In this work, a tool specifically for sizing off-grid hybrid renewable energy systems has been developed. The main feature of this tool is to assist project managers to visualise and evaluate the trade-offs between batteries and diesel generator usage, given a site specific resource availability and load demand. As far as the author is aware, other hybrid system sizing tools do not have the capability of demonstrating their results with the proposed approach. The process of seeking the optimum configuration is demonstrated graphically which allows the hybrid system developer to understand the sizing methodology and trade-offs in a system. Similar graphical approach has been adopted in [7,12] as part of their result's analysis, however it has not been used on analysing the trade-offs between batteries and diesel generator usage. In this paper, the methodology of sizing the hybrid system which considers financial viability and technical performances are outlined. The hybrid system components and life-cycle cost modelling utilised in this work are first explained. In particular, the wind turbine and solar panel are represented mathematically with their coefficients obtained empirically from the measured wind speed, solar irradiation and their respective output power data. Then, the optimum configuration of a hybrid system is obtained based on minimum life-cycle cost. It is then followed by the load sensitivity towards the cost and the overall performance of the hybrid system. The corresponding sensitivity analysis on batteries and diesel generator utilisation throughout the year are shown as part of the discussion.

## 2. Modelling of hybrid system components

As mentioned before, a graphical user interface (GUI) has been developed which assists the project manager to analyse the long term costs of energy production of a hybrid system. This potentially helps developers to make a justifiable components sizing decision by taking into consideration of the financial, renewable resources and technical factors. Fig. 1 shows the block diagram of the proposed hybrid system implemented in this work. The power flow directions are indicated with the arrows. In this research, the wind turbine and the PV systems are modelled using empirical data, which directly correlates the relationship between renewable resources and generated power output. Thus, the losses of the system are accounted in the equation. Similarly, the efficiency of the diesel generator is related by its power output and its fuel consumption. The modelling approach of these systems will be further described in the following sections. For the case of the grid-forming inverter, it is assumed that it has an average operational efficiency of 95%. The widely employed lead-acid batteries are considered in this study. Lead-acid batteries typically have coulombic

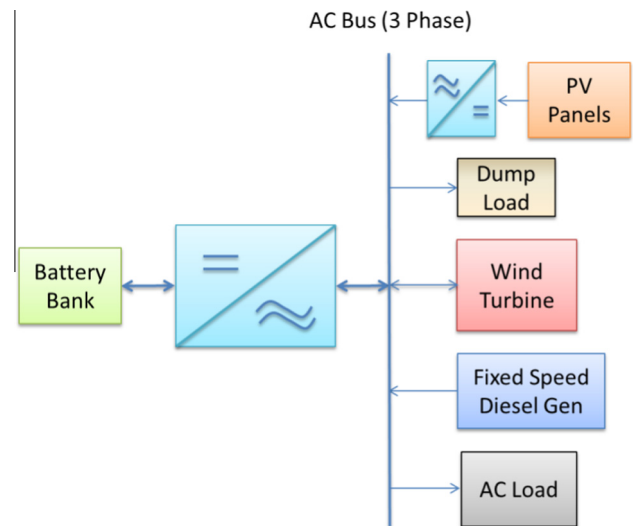


Fig. 1. Proposed hybrid wind-PV-diesel system.

(Ah) efficiencies of around 85% and energy (Wh) efficiencies of around 70% over most of the state of charge (SOC) range [13]. These parameters are determined by the details of design and duty cycle to which they are exposed [13]. In the following case studies, a round-trip efficiency of 70% is adopted.

The layout of the GUI is demonstrated in Fig. 2. The load profile, amount of wind turbines and PV panels, battery parameters, inflation and discount rate, cost of components, and wind turbine and PV panel coefficients can be altered before performing life-cycle cost simulation. In addition, the user is able to load yearly renewable resources such as wind speed and solar irradiation for the interested site. In order to simplify matters, the renewable energy resources and load are assumed to be same throughout the 20 years lifetime. With all the information given to the GUI programme, the optimal batteries and diesel generator sizes are sought. The following subsections describe the modelling of the system components, such as the wind turbine and PV panels, and also load profile and system operation modelling.

It is important to note that the developed sizing tool is generic and it is suitable to be used for different types of wind turbines and solar panels. In addition, generalised wind turbine and solar system power curves can be used if needed. This can be achieved by keying in the particular power curve's coefficients within the GUI. However, the author has adopted a Gaia-Wind wind turbine and Sanyo solar panels as an example in this work due to the data availability on both systems. The modelling approach and analysis carried out in the following sections can serve as a reference and can be modified to suit any other systems of interest.

### 2.1. Wind energy modelling

As stated before, the renewable energy conversion systems (wind and PV) is represented with the power curve's coefficients. For the case of wind energy systems, most of the small wind turbine manufacturers do provide their wind turbine power curves as part of the associated data sheets. By plotting an estimated power curve and interpolating it with a polynomial equation, the coefficients can be obtained. Higher resolution power performance data are published and readily available if the wind turbines are accredited by certification body such as TUV NEL, Small Wind Certification Council (SWCC) and National Renewable Energy Laboratory (NREL).

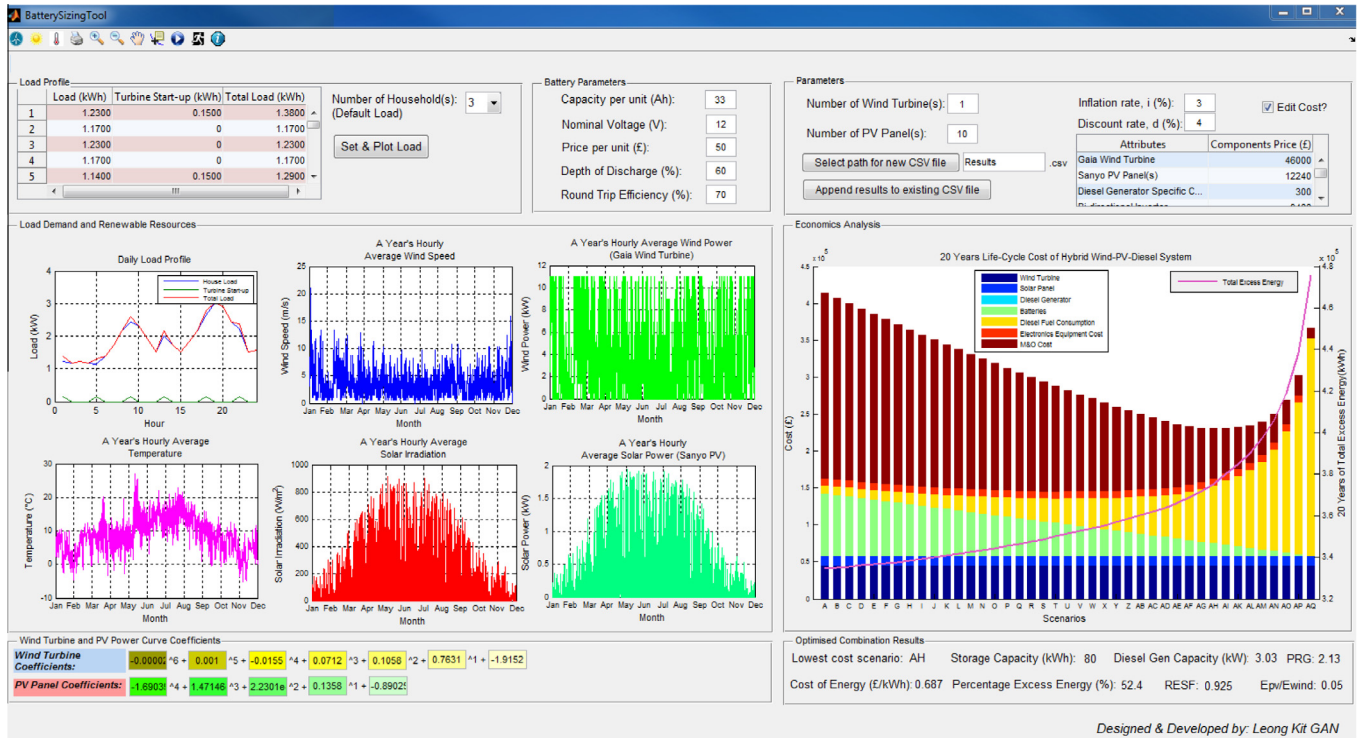


Fig. 2. GUI for calculating long term cost on hybrid system operation.

The wind turbine generated power here is modelled based on Gaia's wind turbine power curve as shown in Fig. 3. The fixed speed wind turbine is rated at 11 kW and utilises an induction machine to generate electricity. The power curve in Fig. 3 is formulated empirically using Gaia's measured wind speed and power output from the wind turbine.

Thus, the output power from Gaia's wind turbine can be computed at any given wind speed using a polynomial function.

A polynomial is a function describing the form of a length of line which is constructed out of known constants and variables. This function uses the operations of addition, subtraction, multiplication and non-negative integer exponents to describe the form of the line. The equation is a function of wind velocity, given as:

$$P_{\text{wind}} = -2e^{-5}V^6 + 0.001V^5 - 0.0155V^4 + 0.0712V^3 + 0.1058V^2 + 0.7631V - 1.9152 \quad (1)$$

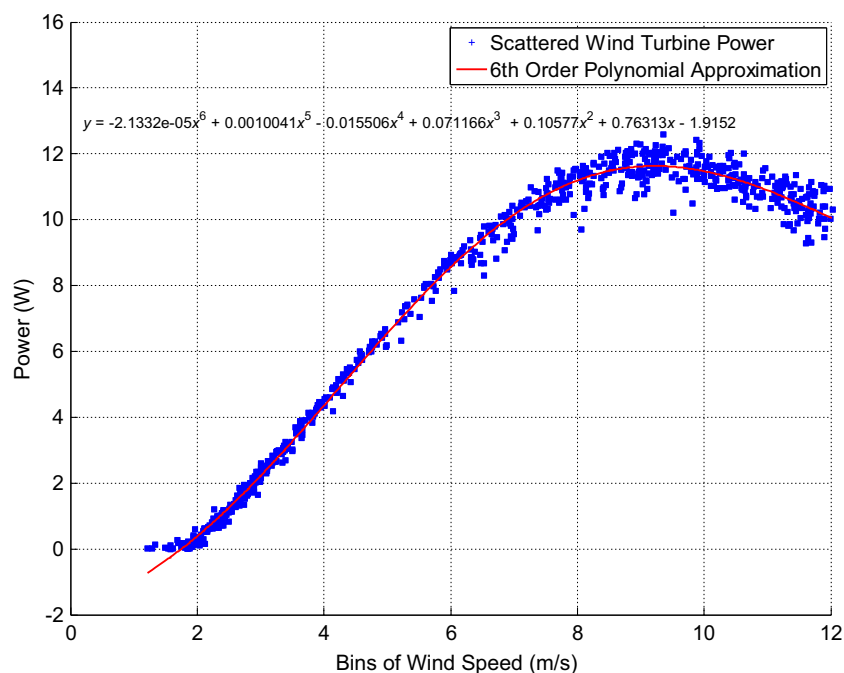


Fig. 3. Gaia's wind turbine approximated power curve.

where

$P_{\text{wind}}$ : Wind turbine output power (kW)

$V$ : Wind velocity (m/s)

It is important to emphasise that power generation starts at wind speeds above 3.5 m/s (cut-in speed) until a rated wind speed of 9.5 m/s is reached. For wind speeds exceeding 25 m/s, the turbine has to be stalled to prevent structural damage [14].

A simple and common approach to represent a wind profile and its output power is by treating samples of wind velocity as a random variable with a Weibull distribution [8,15]. In the sizing process of distributed energy sources, the wind uncertainty is represented with the Weibull probability density function [16]. This approach can be visualised in Fig. 4 [17]. The energy output can be computed by multiplying the formed Weibull distribution with the wind turbine power curve. However, it was observed that there were some discrepancies in the fitted Weibull distribution curve [15]. In addition, this approach would not be used to perform time series simulation as the yearly wind profile is statistically modelled. Therefore, the overall optimisation of the hybrid system can be compromised as a result this inaccuracy [18].

In order to simulate the operation of the hybrid system [19,20], the measured data of hourly wind speed is utilised. The benefit of using annual hourly data is that the peaks and troughs of the wind speed profile are included, thus reflecting a more realistic situation. Moreover, variations in seasonal wind speed are also taken into account when running the simulation. Hourly wind speed data

measured at Bishopton [21], which is situated in the north east of Renfrewshire, Scotland is depicted in upper plot of Fig. 5. The first hour begins on 1/1/2012 at 00:00. The wind is measured in open terrain at a height of 10 m above ground level [21].

The Gaia Wind 11 kW wind turbine is used in this study; hence the power curve from Fig. 3 is used to compute the power output for the turbine. The corresponding wind power over a one year period is shown in the lower plot of Fig. 5. This takes into account the cut-in and cut-off wind speed supplied by the manufacturer. In this case, it can be seen that the maximum output power is regulated to 11 kW.

## 2.2. Solar energy modelling

In order to formulate a PV system power curve, the analytical approach is not chosen here due to its complexity in matching the manufacturer's solar panel performance. Instead, the power curve of a PV system (AC power vs solar irradiation) can be estimated using the following approach if the real measurements are not available.

Generally,  $I$ - $V$  characteristics for different level of solar irradiances are publicly available. An example of such plot is shown in Fig. 6. For a particular solar irradiation level, a maximum power point can be identified. Extracting the maximum power values for all the available irradiances, the maximum cell power versus solar irradiation is obtained, as displayed in Fig. 7. Wire and connection losses, auxiliary power consumption (such as controller

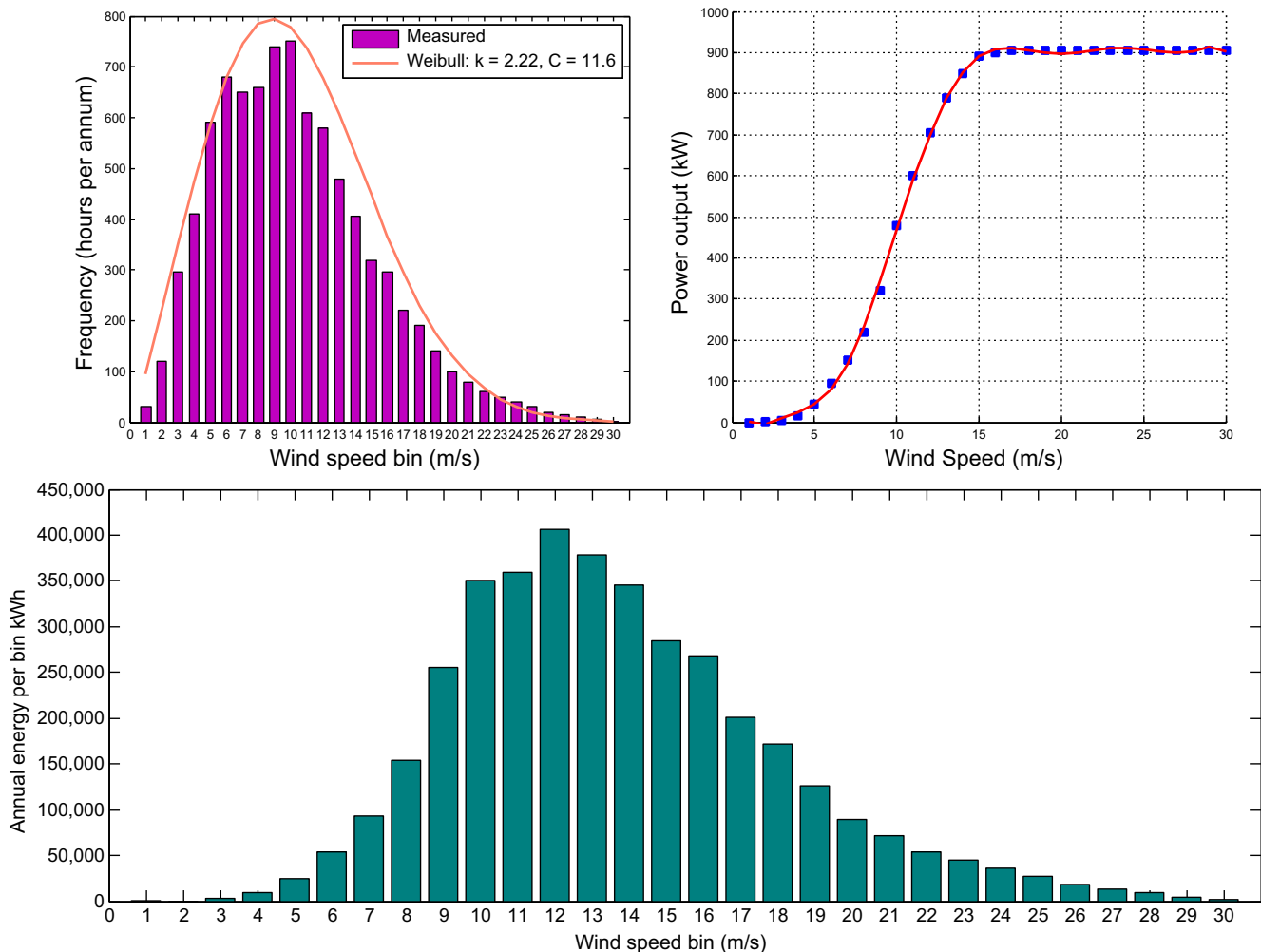


Fig. 4. (a) Annual wind speed distribution, (b) wind turbine power curve, (c) annual power output.



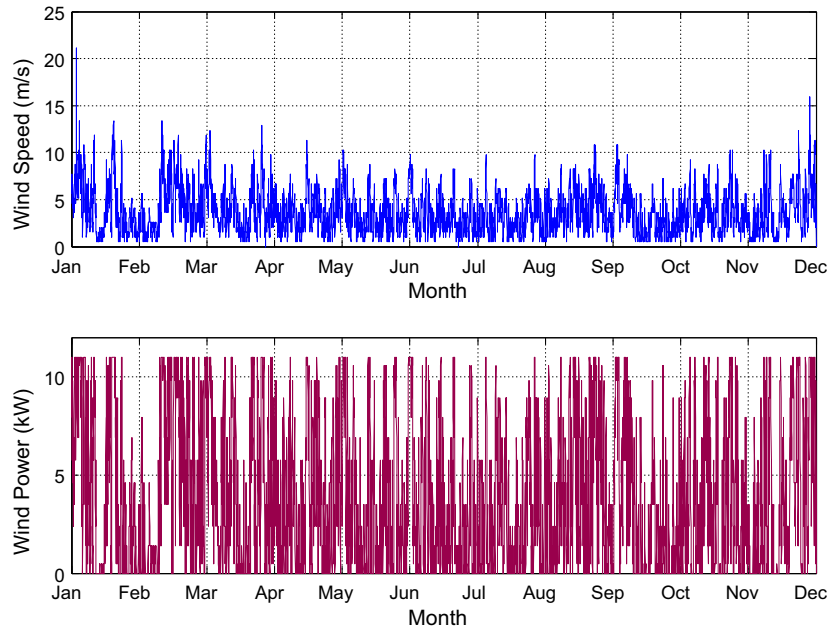


Fig. 5. Hourly wind speed (top) and wind power (bottom) in Bishopton, 2012.

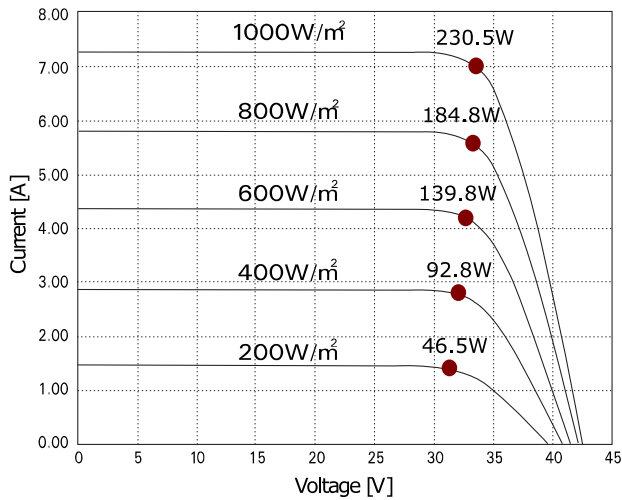


Fig. 6. Current–voltage characteristics of a heterojunction with intrinsic thin layer PV module (Sanyo) across a variations of solar irradiance, characterised at cell temperature of 25 °C [23].

or sun tracker), battery charge-discharge efficiency, dust on the array, and inverter and line losses should be taken into consideration in order to improve the accuracy of the estimated usable power output. Usually, these losses are approximately 10–20% [22]. Note that the described methodology only valid with the assumption that the interested system has the capability of tracking the maximum power for all solar irradiation levels.

In this example, the PV system modelling is similar to the wind energy modelling as discussed previously, which is formed empirically. Fortunately, the empirically obtained AC power output as a function of the solar irradiance power curve is adopted here due to the data availability from previous work [24]. Therefore, the above-mentioned losses and non-ideal environmental factors are taken into consideration. In this case, the Sanyo HIT thin film PV panels were modelled as part of a PV system with inverters to form an AC output. The Sanyo PV panel specifications are listed in Table 1.

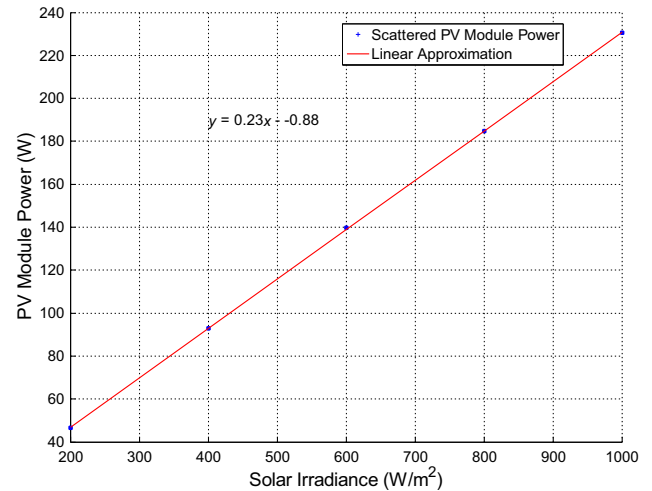


Fig. 7. Maximum cell power vs solar irradiation.

Table 1

Sanyo HIP 230 Thin Film – HIT parameters.

Parameters	Sanyo HIP 230 Thin Film – HIT
Maximum power point current, $I_{mp}$ (A)	6.71
Maximum power point voltage, $V_{mp}$ (V)	34.3
Maximum experimental peak power, $P_{max, e}$ (W)	230.153
Maximum model peak power $P_{max, m}$ (W)	230.15
Short circuit current, $I_{sc}$ (A)	7.22
Open circuit voltage, $V_{oc}$ (V)	42.3
Reverse saturation current, $I_o$ (A)	$8.49E-12$
PV current, $I_{pv}$ (A)	7.239
Diode ideality constant, $a$	1.0
Shunt resistances, $R_p$ ( $\Omega$ )	183.33
Series resistances, $R_s$ ( $\Omega$ )	0.4862

The model is developed with the power output (W) delivered to the grid as a function of solar irradiance ( $W/m^2$ ) at standard test conditions of 25 °C and 0 m/s wind speed, as shown in Fig. 8 [24].

In Fig. 8, the output power of the PV system can be computed at any given solar irradiation using the polynomial function. The equation is a function of solar irradiance, given as:

$$P_{\text{solar}} = -1.69e^{-10}X^4 + 1.47146e^{-7}X^3 + 2.2301e^{-5}X^2 + 0.1358X - 0.89025 \quad (2)$$

where

$P_{\text{solar}}$ : PV panel output power (W)

$X$ : Solar irradiance (W/m<sup>2</sup>)

Similar to all other semiconductor devices, the PV panels (formed by many solar cells) are sensitive to temperature. From the characteristic curves, it can be demonstrated that the parameter which is most influenced by the variations of temperature is the

open-circuit voltage. The impact of such parameter on the Sanyo PV panel is shown in Fig. 9. As indicated, the variations in open-circuit voltage as a function of temperature is relatively more significant than its corresponding short-circuit current. Therefore, in order to minimise the PV power computation error from a given solar irradiation level, the variation in ambient temperature is taken into consideration.

The power output of a solar panel can be defined as the product of its terminal voltage and current. The methodology to include the temperature effect on the power output is performed by utilising the open-circuit voltage percentage error as a factor of adjustment. This error is calculated with respect to the standard condition's (at 25 °C) open-circuit voltage, which is approximately 42.5 V. The plot in Fig. 10 is derived from Fig. 9 by interpolating the

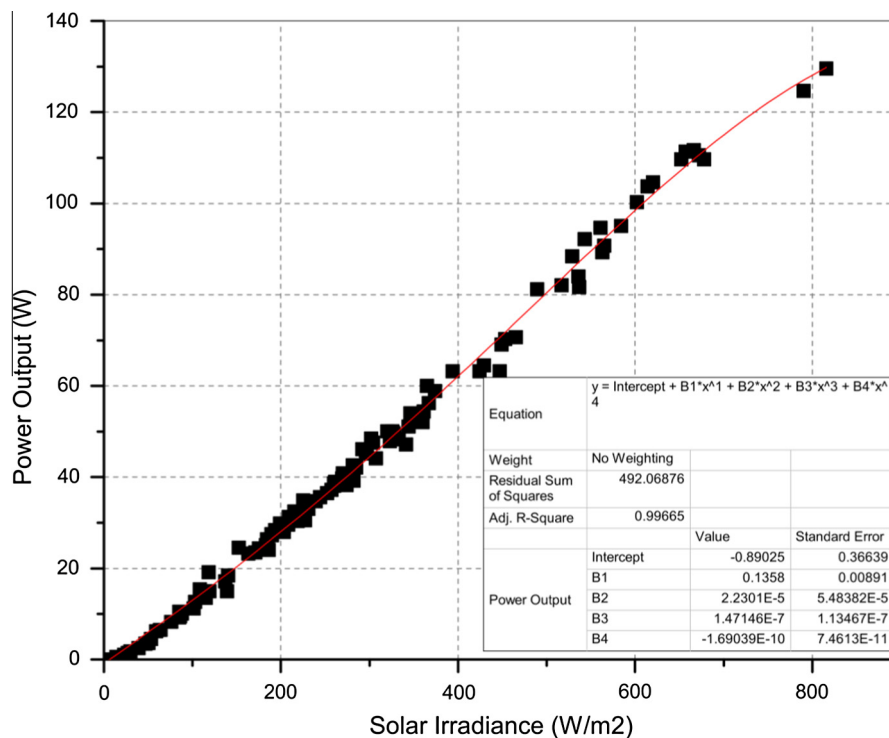


Fig. 8. Thin Film HIT system power output vs solar irradiance at 25 °C, 0 m/s [24].

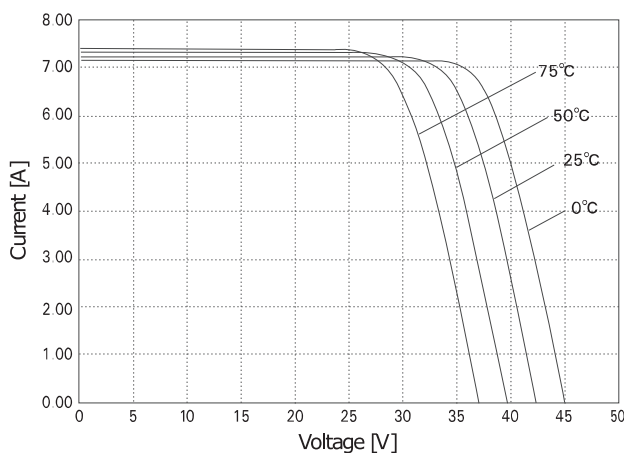


Fig. 9. Current-voltage characteristics of a HIT PV module (Sanyo) across different temperatures.

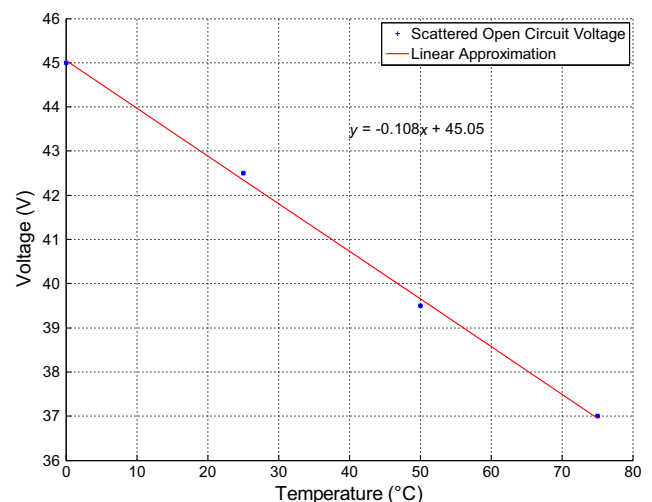


Fig. 10. HIT solar panel open-circuit voltage vs temperature.

open-circuit voltages across the temperature range. The open-circuit voltages correspond to different temperature levels can be identified from the formulated linear equation.

An example to compute the power output for a given solar irradiation of  $600 \text{ W/m}^2$  at  $0^\circ\text{C}$  is illustrated. From Fig. 8, it can be noted that the maximum power output from a solar irradiation of  $600 \text{ W/m}^2$  at  $25^\circ\text{C}$  is given as:

$$P_{\text{solar}@25^\circ\text{C}} = 100 \text{ W} \quad (3)$$

At  $0^\circ\text{C}$ , the open-circuit voltage of the PV panel is  $45.05 \text{ V}$ . Therefore, the percentage error of the open-circuit voltage with respect to standard condition open-circuit voltage can be defined as:

$$\text{error} = \frac{45.05 \text{ V} - 42.5 \text{ V}}{42.5 \text{ V}} \times 100\% = 6\% \quad (4)$$

As a result, the power output of the PV panel with solar irradiation of  $600 \text{ W/m}^2$  at  $0^\circ\text{C}$  can be corrected to:

$$P_{\text{solar}@0^\circ\text{C}} = 100 \text{ W} \times 106\% = 106 \text{ W} \quad (5)$$

The hourly temperature and solar irradiation are measured from the same location as the wind speed data. This is graphically shown in Fig. 11 [21]. As expected, the solar irradiation reaches its peak values during the summer and is at a minimal level during the winter. The corresponding AC solar power from the PV system (which consists of ten Sanyo solar panels and inverters) is portrayed in the lower plot of Fig. 11.

### 2.3. Load profile modelling

The consumer load profile gives a total of  $15 \text{ kWh}$  per day. In addition, induction generators require a high inrush current during start-up process. Therefore, the start-up energy of the wind turbine is taken into account and is given as:

$$P = \sqrt{3} \times 415 \text{ V} \times 100 \text{ A} = 71.88 \text{ kW} \quad (6)$$

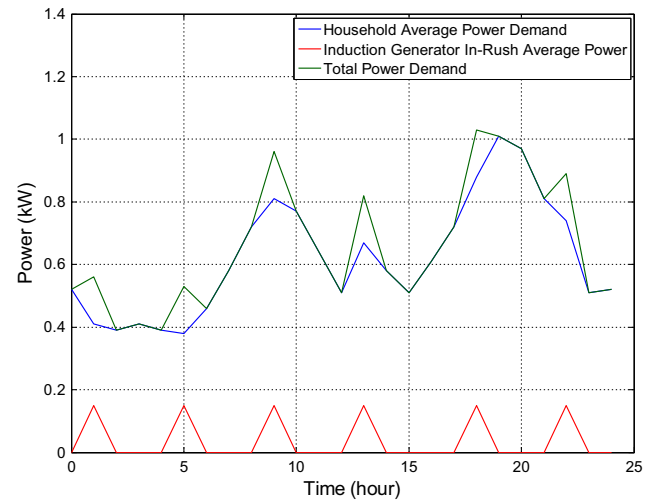


Fig. 12. Load profile (consumer plus Gaia's wind turbine start-up).

$$E = \frac{71.88 \text{ kW} \times 7.5 \text{ s}}{3600 \text{ s}} = 0.15 \text{ kWh} \quad (7)$$

In this study, the start-up stator current is assumed to be  $100 \text{ A}$ . Without a soft-starter, the start-up process completed in approximately  $7.5 \text{ s}$ . Typically, the wind turbine start-up process will take place several times a day. This study assumes that start-ups occur 6 times each day, distributed evenly throughout the  $24 \text{ h}$ . Fig. 12 shows the consumer, wind turbine start-up and total load power throughout the day. For simplicity, it is being repeated 365 times to emulate annual demand. However, if a more accurate load model is desired, it can be formulated from historical measurements with the incorporation of load growth factors. Considering a single to a few households of electricity demand to be supplied from the off-grid system, the simplified load model here is suffice as the load growth factor has a stronger influence on the design of large scale power systems.

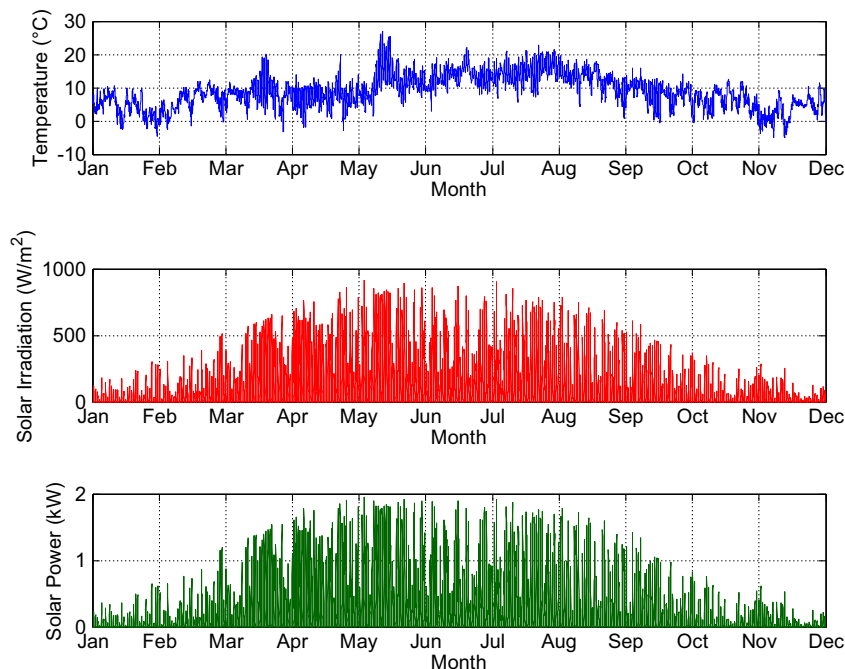


Fig. 11. Hourly solar irradiation (top) and solar power (bottom) in Bishopton, 2012.



## 2.4. Battery storage calculations

In a hybrid wind–PV–diesel system, battery banks are electro-chemical devices that store energy from other AC or DC sources for later use. The batteries serve as a platform to maximise the usage of renewable energy by storing excess energy whenever the supply from the wind turbine(s) and solar panel(s) exceeds the load demand. Furthermore, a properly-sized battery bank is capable of reducing the number of start–stop cycle of the diesel generator, along with a reduction in fuel consumption.

When determining the SOC for an energy storage device, the following constraint must be satisfied.

$$SOC_{\min} \leq SOC \leq SOC_{\max} \quad (8)$$

where  $SOC_{\min}$  and  $SOC_{\max}$  are the minimum and maximum state of charge respectively. This research assumes that  $SOC_{\min}$  and  $SOC_{\max}$  are equal to 40% and 100% respectively. Note that the diesel generator is switched-on only whenever the energy in the batteries is fully dissipated in addition to insufficient generation from the renewables to meet the demand. Since the diesel generator is not used to charge the batteries here, the energy generated from the diesel generator should be excluded in the battery storage calculation. The following describes the procedure of sizing the batteries.

The adopted approach to size the batteries is laid out in [5]. The magnitude difference between generated power ( $P_{\text{gen}}$ ) and the demand ( $P_{\text{dem}}$ ) over a given period of time is:

$$\Delta P = P_{\text{gen}} - P_{\text{dem}} \quad (9)$$

The power equation can then be translated into energy generated and demanded ( $W_{\text{gen}}$ ,  $W_{\text{dem}}$ ) over a period of a year (8760 h) and be written as:

$$W_{\text{gen}} = \sum_{n=1}^{8760} [(\Delta T)(K_w P(n)_w + K_s P(n)_s)] \quad (10)$$

$$W_{\text{dem}} = \sum_{n=1}^{8760} [(\Delta T)(P(n)_{\text{dem}})] \quad (11)$$

where  $K_w$  and  $K_s$  represents the number of wind turbines and PV panels used,  $n$  is the sampling time (hour of year), and  $\Delta T$  is the time between the samples (in this case one hour).

In order to achieve the balance between generation and demand over a period of time, the curve of  $\Delta P$  versus time must have an average of zero over the same time period. Note that positive values of  $\Delta P$  indicate the availability of generation and negative  $\Delta P$  indicates generation deficiency. The energy curve can be obtained by integrating  $\Delta P$ .

$$\Delta W = \int \Delta P dt = W_{\text{gen}} - W_{\text{dem}} \quad (12)$$

The energy curve of Eq. (12) can be used to find the required storage capacity for the hybrid system.

On an average year, the battery is required to cycle its charge between the positive and negative peaks of the energy curve. Therefore, the battery should be sized at least equal to the difference between the positive and negative peaks of the energy curve, as shown in Eq. (8).

$$\text{Required Storage Capacity} = \text{Max} \int \Delta P dt - \text{Min} \int \Delta P dt \quad (13)$$

As aforementioned, the batteries are limited to cycle between 40% and 100% in this work. Therefore, the number of batteries required for the needed storage capacity is computed as:

$$\text{Number of batteries} \geq \frac{\text{required storage capacity}}{0.6 \times \text{rated capacity of each battery}} \quad (14)$$

## 2.5. System operations modelling

The following energy-production scenarios exist within the hybrid system:

- The energy is produced by the wind turbine and solar panels are directly sent to the consumer load.
- Diesel generator is operated (brought online) at times when wind power and solar power fail to satisfy load demand and when battery storage is depleted.
- The surplus energy from wind turbine and solar panels (not absorbed by consumer load) is stored in the batteries via the bi-directional inverters.
- The stored energy in batteries is used to cover the energy deficit.
- The excess energy is dissipated by a dump load if the batteries SOC are at their maximum level.

## 3. Life-cycle cost modelling

This section describes the life-cycle cost modelling for the considered case study. These include hybrid system hardware cost, operation and maintenance (O&M) cost and long term diesel cost.

### 3.1. Hybrid wind–PV–diesel system hardware cost estimation

The initial estimated cost of components involved in implementing the hybrid wind–PV–diesel system is listed in Table 2. The high cost incurred by the SMA bi-directional inverters is due to the topology proposed in this work i.e. battery grid-formed requirement. During the start-up process of the induction generator, high current will be transferred from the batteries. The high power transferred translates to the high cost of the converter.

### 3.2. Operation and maintenance (O&M) cost estimation

The O&M cost of a hybrid wind–PV–diesel system can be significant when considering for a long term operation as highlighted in [7]. In the case of studying economics between batteries and diesel generator capacity (directly proportional to fuel consumption), the consideration of O&M cost is important as they inherit different price characteristics. For instance in this work it was assumed that the batteries (lead-acid) will need to be replaced every 5 years [30]. Longer lifetime is possible to be achieved with careful operation of the batteries, such as limited charge rates, limited weekly cycling, occasional re-conditioning of the batteries, and controlled temperature [31]. On the contrary, diesel generators which are relatively inexpensive compared to its operating fuel costs for 20 years, is assumed to be renewed every 7 years [32]. The assumptions made here are based on past experiences. As the technologies improve over time, these assumptions should be altered accordingly.

The O&M costs are incurred at later times, thus it is convenient to refer all costs to the time of acquisition i.e., present worth. The inflation rate,  $i$  and discount rate,  $d$  are the two factors which affect the value of money over time. The present worth factor of an item that will be purchased  $n$  years later is given by [33]

**Table 2**  
Hardware cost estimation of a hybrid wind–diesel system [25–29].

Components	List price (£)
Gaia wind turbine system	46,000.00/unit
Sanyo PV system	1224.00/unit
3-Phase SMA grid-forming inverter cluster	9468.00/unit
Diesel generator specific cost	300/kW
Battery (12 V, 33 Ah)	50/unit

$$P_r = \left( \frac{1+i}{1+d} \right)^n \quad (15)$$

The present worth (PW) is thus:

$$PW = (P_r)C_0 \quad (16)$$

where  $C_0$  is cost of an item at the time the investment was made.

Sometimes it is necessary to determine the present worth of a recurring expense, the cumulative present worth factor can be derived as [33]:

$$P_a = \left( \frac{1-x^n}{1-x} \right) \quad (17)$$

where  $x = \left( \frac{1+i}{1+d} \right)$ .

If the recurring purchase does not begin until the end of the first year, and if the last purchase occurs at the end of the useful life of the system, there will still be  $n$  purchases, but the cumulative present worth factor becomes

$$P_{a1} = xP_a \quad (18)$$

In this work, the 20 years cumulative maintenance cost of the wind turbine and solar panels utilise the present worth factor,  $P_{a1}$ . The wind turbine and solar panels yearly maintenance cost are £500 and £100 respectively. It is assumed that the batteries and power electronics components (inverters) need to be replaced every 5 years [30] and 10 years, respectively. Finally, the diesel generator is assumed to be replaced every 7 years. For the given inflation rate of 3% and discount rate of 4%,  $x = 0.9904$ ,  $P_a = 18.27$ , and  $P_{a1} = 18.1$ . So Table 3 can now be generated.

### 3.3. Diesel generator fuel consumption modelling

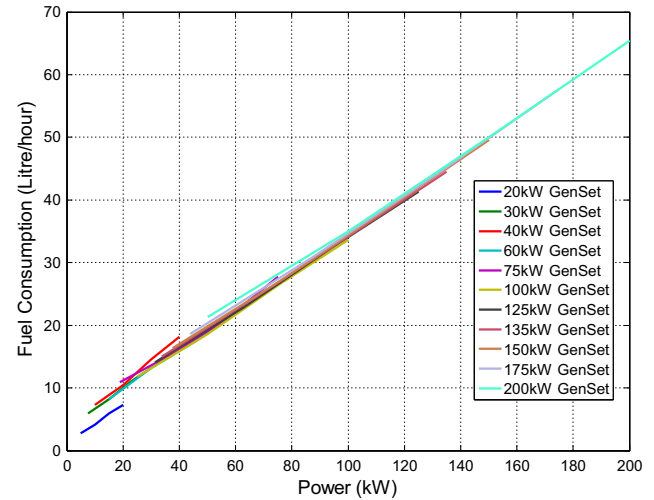
In order to justify the long term economics of diesel generators in a hybrid system, it is important to understand the diesel fuel consumption for different generator capacities and also the future diesel price.

Unfortunately at present, most of the small diesel generator (sufficient for single household) manufacturers do not include the  $\frac{1}{4}$ ,  $\frac{1}{2}$ ,  $\frac{3}{4}$  and full load fuel consumption in their data sheet. Thus, we have approximated the fuel consumption for various sizes using the following approach. Fig. 13 shows the plots of approximated diesel generator fuel consumption (litres/hour) at  $\frac{1}{4}$ ,  $\frac{1}{2}$ ,  $\frac{3}{4}$  and full load, starting from a power rating of 20 kW up to 200 kW. Rather than using a specific manufacturer's diesel fuel consumption data, these empirical data [34] were obtained from Diesel Service & Supply Ltd. (more than 30 years of history), which it is believed to be realistic and not brand bias.

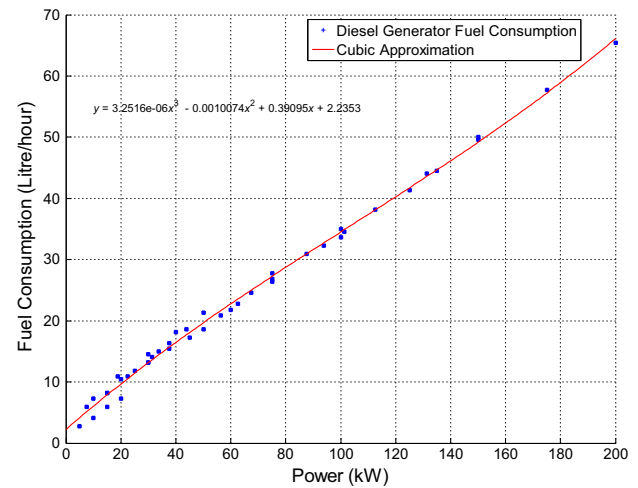
It is observed that the fuel consumption coincides with each other. From here, all the generator's fuel consumption points are plotted and cubic fitting is performed, as shown in Fig. 14.

**Table 3**  
Operation and maintenance cost [25,27–29].

Component	Initial cost (£)	Present worth (£)
Gaia wind turbine maintenance for 20 years	500/year	9050
PV panels maintenance for 20 years	100/year	1810
Battery at year 5	50/unit	47.6/unit
Battery at year 10	50/unit	45.4/unit
Battery at year 15	50/unit	43.3/unit
Diesel generator at year 7	300/kW	280.38/kW
Diesel generator at year 14	300/kW	262.05/kW
SMA grid-forming inverters at year 10	9468.00/unit	8596.00/unit



**Fig. 13.** Diesel generator fuel consumption for various capacity.



**Fig. 14.** Cubic fit of diesel generator fuel consumption.

The approximated fuel consumption equation as a function of power, given as:

$$F = 3.2516e^{-6}P^3 - 0.0010074P^2 + 0.39095P + 2.2353 \quad (19)$$

In order to verify the accuracy and reasonability of the obtained fuel consumption equation, we compared it with other available sources, i.e. Cummins Power Generation's diesel generator set datasheet [35] and Hardy Diesel Ltd. [36]. A first derivative of the above function gives per kW fuel consumption for the above power rating range (0–200 kW), as shown in Fig. 15 (blue<sup>1</sup> curve). The concave upward shape is attributed to the first derivative of the third order equation. Interestingly, the least fuel consumption operation is at 100 kW.

Based on literature [34,35], a diesel generator typically consumes between 0.28 and 0.4 l of fuel per kilowatt hour at the generator terminals, which are marked as red (Lower Limit) and green (Upper Limit) constant lines respectively. On top of that, Hardy Diesel Ltd. uses 0.383 l [36] of fuel per kilowatt for their reference in calculating fuel consumption. Therefore, it can be seen that the

<sup>1</sup> For interpretation of color in Fig. 15, the reader is referred to the web version of this article.

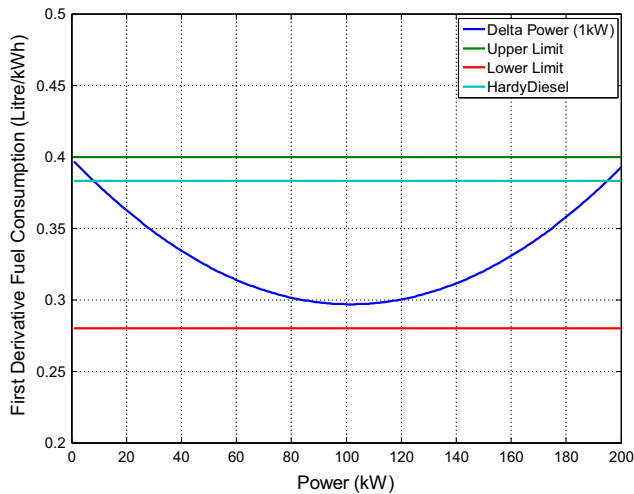


Fig. 15. Comparison of first derivative and other sources fuel consumption plots.

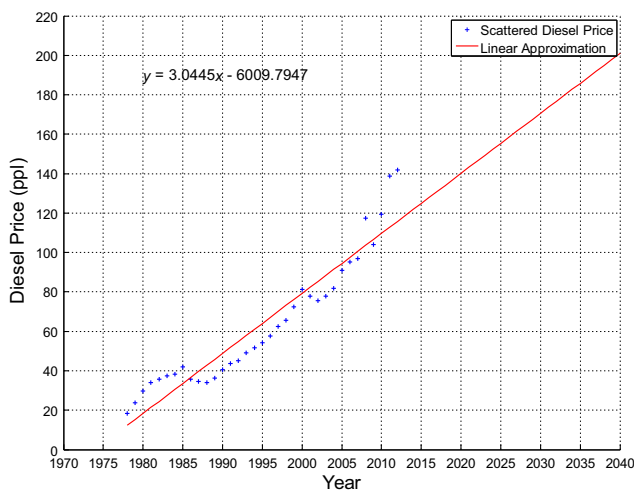


Fig. 16. Linear extrapolation of diesel fuel price (pence per litre).

diesel generator set's fuel consumption estimation from this work is within the boundary compared to other sources.

For this case study, we are interested in estimating the long term energy-production (from year 2014–2034) cost involved in running the hybrid system. Therefore, predicting the future diesel fuel price is essential. Fig. 16 shows the historical scatter plot of diesel fuel price (pence per litre) in the UK [37]. The future diesel price might be lower than the predicted values as renewable energy penetration becomes higher in the future, causing demand on fossil fuel to drop. For simplicity, a linear approximation line is extrapolated to 2040.

The diesel price as a function of year is given as:

$$\text{Price} = 3.0445 \times (\text{Year}) - 6009.8 \quad (20)$$

With the fuel consumption and diesel price equations, we are able to compute the cost of running the diesel generators for various capacities in different years.

## 4. Results and discussion

### 4.1. Scenarios analysis

Using the abovementioned models and costs, various combination sets of batteries and diesel fuel consumption have been

simulated, as depicted in Fig. 17. Each bar shows the lifetime cost (from 2014 to 2034) of running the hybrid wind–PV–diesel system in the Bishopton area.

All the scenarios utilised an 11 kW Gaia wind turbine and ten Sanyo PV panels each rated at 230 W. The storage capacity is linearly reduced starting from scenario A up to scenario AQ, as shown in the fourth stack (green colour) from the bottom. The left y-axis is the total cost, while the right y-axis is its corresponding total energy dissipated in dummy loads. It is interesting to note that the diesel generator cost is relatively low compared to its fuel consumption, depending on usage. Thus, it is important for both consumer and project manager to look at life-cycle cost analysis, which points out the high cost being associated with diesel fuel and not the hardware itself.

Scenario A (extreme left column stack) simulates most batteries compared to other scenarios, thus dumping least energy throughout the 20-year period. In addition, the diesel fuel consumption is zero and this can be attributed to the large amount of renewable energy and low load demand. It seems that this is ideal as the load is fully supplied by renewable sources. However, the high incurred cost of batteries and the O&M cost do not justify its financial attractiveness. On the contrary, the diesel-only solution (scenario AQ) demonstrates the power deficit is fully met with diesel generator and consists of no batteries at all. The O&M cost are considerably low as it is only being associated with the replacement of diesel generator and yearly wind turbine O&M cost. However, the total cost is the highest amongst all the simulated scenarios due to the high fuel prices. Furthermore, the excess energy equally is the highest as there are no batteries to store excess energy from the wind turbine and solar panels. The zero-oil solution is not shown in this diagram as it can be imagined that the battery storage required to meet the demand will be very large and costly.

It is clear that the amount of batteries is inversely proportional to the diesel fuel consumption. More batteries means better utilisation of wind power but at the same time it might not be cost effective. The O&M cost is largely attributed to the replacement of batteries and power electronics devices. As fewer batteries are being installed in the system, the O&M cost remarkably reduces. It is important to emphasise that this study does not consider externalities such as environmental impact from fossil fuels. It is beyond the scope of this work to consider this and it is not a straightforward calculation.

From Fig. 17, the optimum configuration obtained for the hybrid wind–PV–diesel system is with 20 kWh battery storage and a diesel generator size of 1.03 kW (Scenario AO). Inevitably, the obtained configuration has struck the balance of batteries and diesel generator usage, giving the lowest cost solution. The optimal solution cost is approximately just under 50% less than diesel-only solution. However, the cost of energy (£/kWh) is approximately £1.10/kWh, far exceeding the cost of utility-generated electricity. Further analysis shows that 83% of the excess energy generated by the RES is not being utilised. This can be explained by the low load demand in the system – generation far exceeds demand. For that reason, the load to be supplied should be increased to reduce excess energy in the system. In addition, it is also noted that most of the simulated scenarios do not justify the use of a diesel generator due to the large amount of excess energy exists within the system. The next section analyses the effects of the load demand changes on the performance of the hybrid system.

### 4.2. Load sensitivity

The performance of renewable energy systems can be characterised by two performance indicators [28]:

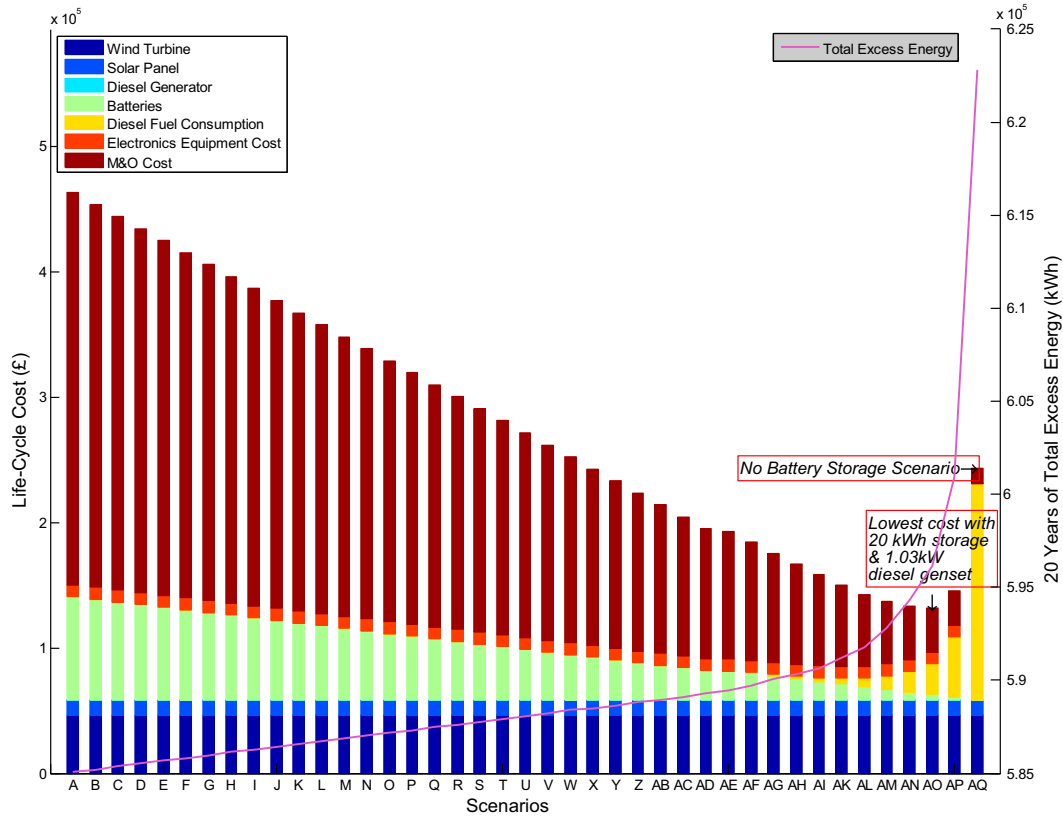


Fig. 17. Life-cycle cost analysis of hybrid wind-PV-diesel system in Bishopton area (single household).

i. Renewable energy sources fraction (RESF), defined by:

$$\text{RESF} = \frac{E_{PV} + E_{WT} - E_{EXC}}{E_{PV} + E_{WT} - E_{EXC} + E_{AUX}} \quad (21)$$

where  $E_{EXC}$  is the excess energy which have been produced and dissipated in resistors and not used for the main load.  $E_{AUX}$  is the energy generated by auxiliary generator, which in this case is diesel generator.

The RESF parameter is also often called solar fraction because wind energy comes from the sun. If  $\text{RESF} = 1$ , it means all the loads are satisfied by RES and no diesel fuel is used.

ii. Gross production (PRG), originating from a solar source (PV + wind) in units of load energy ( $E_L$ ) is defined by:

$$\text{PRG} = \frac{E_{PV} + E_{WT}}{E_L} \quad (22)$$

Here, investigation is carried out on the effects of increasing the load linearly (number of households) towards the performance and financial attractiveness of the hybrid system. The defined hybrid system consists of one Gaia wind turbine and ten Sanyo PV panels. Simulations are performed and only the lowest life-cycle cost solution will be selected for each set of load demand. Fig. 18a–e shows the plots of the described parameters versus the number of households.

From Fig. 18a, it is observed that the cost of energy drops by 32% when the household is increased from one to two. This proves the hypothesis made in the previous section i.e. as the generation capacity matches closer to the load demand, less energy is being dumped (Fig. 18b) and thus drives towards better economics of the hybrid system. Interestingly, as the number of households continue to increase, the cost of energy drops and then picks up when the number of households equal to five. The rise is due to the heavy

reliance of diesel generator in supplying the high demand. In other words, the reduction of renewable energy contribution in the system as the load demand increases is portrayed in Fig. 18c. The PRG (ratio of renewable energy generation to load demand) decreases exponentially as the load increasing linearly, as shown in Fig. 18d.

Based on the cost of energy plot, the optimum number of households to be supplied by the defined hybrid system is three. However, it is observed that it utilises the second most storage capacity. The storage capacity for three households is 38% more than the three household's, but the cost of energy's decrement rate is minimal, as demonstrated in Fig. 18a. So, one should be flexible in allocating the number of batteries in households as this could potentially affect the batteries' lifetime. From the author's point of view, two to three households are reasonable loads to be supported by the system. Fewer households also ensure better utilisation of clean energy as a source of electricity compared to diesel fuel, which is indicated by REFS. Moreover, on a yearly basis, an optimised hybrid wind-PV-diesel system produces more energy than the load demand and quite significant amount of the energy produced by both the wind turbine and PV panels is lost, owing to the necessity to reach an LOLP equal to zero (giving total autonomy).

#### 4.3. Hybrid system technical performance analysis

It is worth exploring the hybrid system operation performance, in particular the batteries SOC and diesel generator start-stop variations. In this section, we use three households load allocation as our case study. The corresponding life-cycle cost scenarios are shown in Fig. 19, with batteries capacity linearly decreasing from scenario A to scenario AQ. It is predicted that as the batteries capacity becomes lower, it charges and discharges more frequently. Smaller storage also means lower SOC are reached

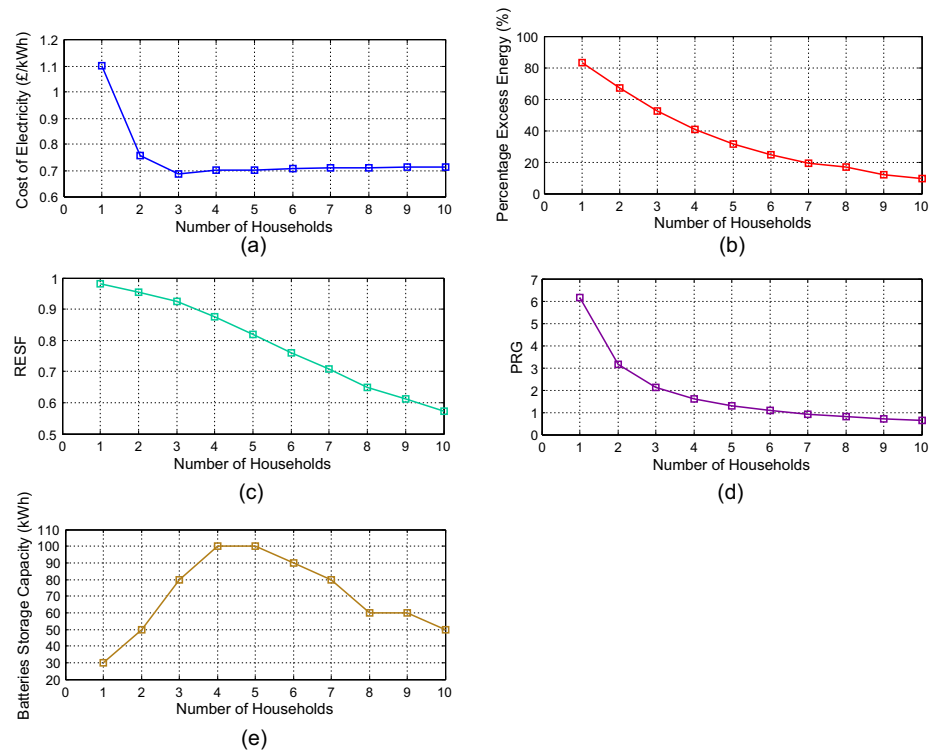


Fig. 18. Performance indicators (a) cost of energy (£/kWh), (b) percentage excess energy, (c) RESF, (d) PRG, (e) number of batteries against number of households.

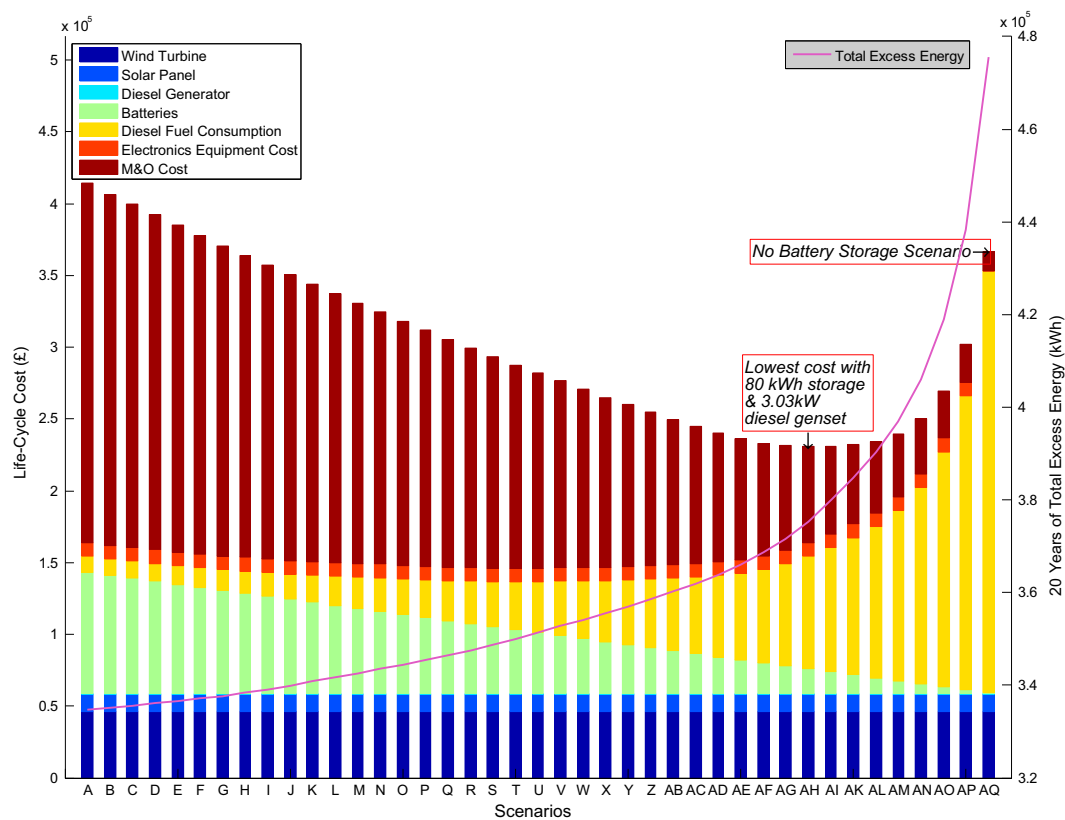


Fig. 19. Life-cycle cost analysis of hybrid wind-PV-diesel system in Bishopton area (three households).



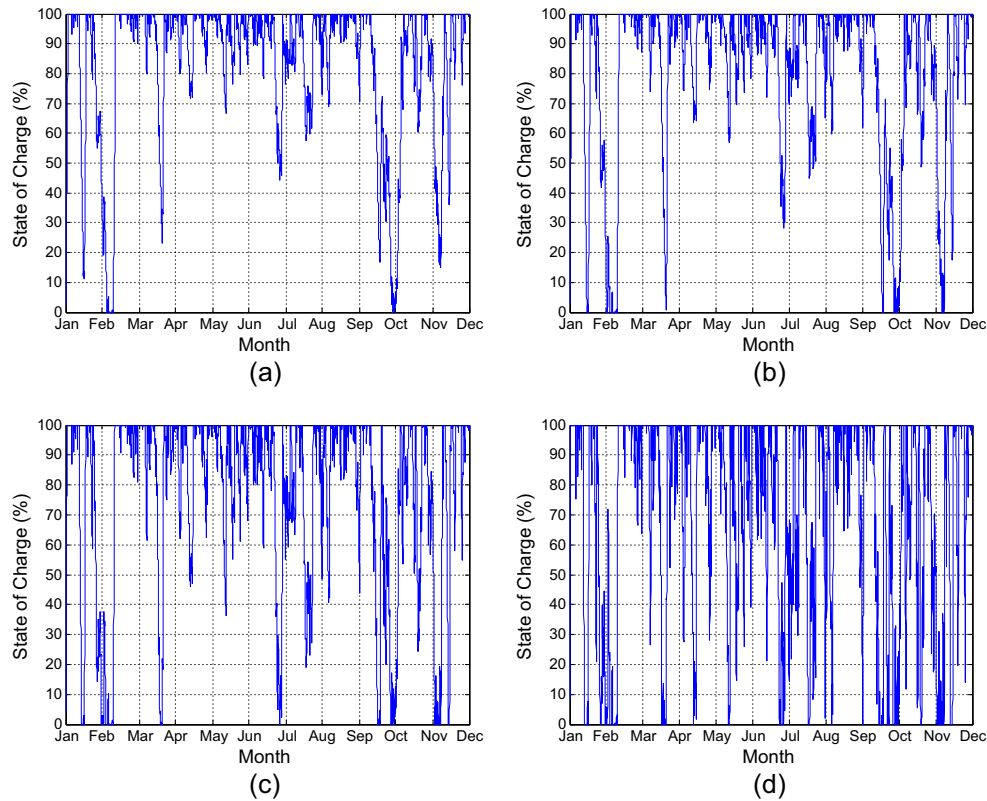


Fig. 20. Yearly batteries SOC for scenario A, J, T and AE (three households).

more frequently, which could potentially shorten batteries lifetime.

Few scenarios (with different battery capacities) are selected to demonstrate the yearly batteries SOC cycles. Fig. 20 shows the yearly batteries SOC for scenario A, J, T and AE, respectively. Intuitively, the batteries discharge and reach zero level more frequently as we move from scenario A to AE. The frequent batteries charge and discharge cycles in scenario AE is more detrimental to its lifetime compared to scenarios with fewer cycles. Besides considering the number of cycles, the depth of cycle also affects the lifetime of the batteries. This can be observed from a typical trend of battery service life in relation to depth of discharge chart, as shown in Fig. 21 [38]. Usually, this information can be obtained from the battery manufacturers. From the observation

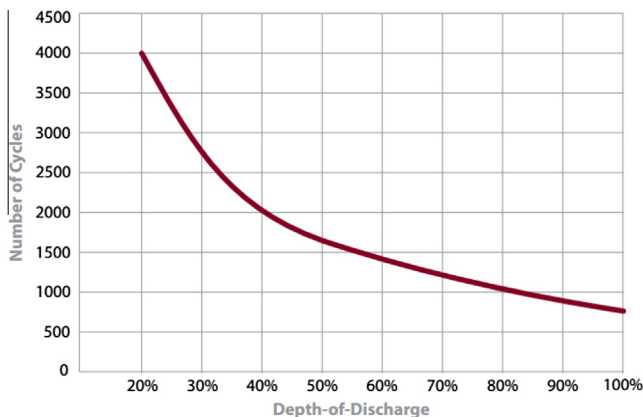


Fig. 21. Typical cycle life curve of a Trojan battery for renewable energy applications [38].

above, it can be concluded that the depth of discharge is higher and more frequent when the system is sized with a smaller battery capacity.

Fig. 22 shows the diesel generator's operating capacity (in percentage of rated capacity) for scenario A, J, T and AE. All scenarios are optimised to have different diesel generator capacities. It is a well-known fact that a fixed speed diesel engine needs to run at least 20–40% of its rated capacity because of technical limitations running it at lower loads in addition to the economics of fuel utilisation [28]. Fortunately, most of the time, the diesel generator operates at more than 20% of its rated capacity for all simulated scenarios. Furthermore, it is observed that the diesel generator runs more frequently as the installed batteries capacity decreases.

Based on the abovementioned analysis, it seems more beneficial for a hybrid system to be sized with a larger battery storage capacity to achieve less frequency charge and discharge sequence and to reduce the start–stop process of the diesel generator. However, a balance should be made between the use of diesel generator and the size of batteries capacity, considering the substantial initial investment and also long term economics of the system. From the author's point of view, the optimum results computed from Fig. 19 (scenario AH) represents the lowest life-cycle cost and at the same time demonstrates a balance in diesel generator and batteries utilisation.

#### 4.4. Hybrid system configuration analysis

In this section, we investigate the financial attractiveness of hybrid wind–PV–diesel system compared with PV–diesel and wind–diesel systems. In this case study, the optimal cost for each configuration is sought. For instance, sensitivity analysis is performed for the PV alone system and only the lowest life-cycle cost will be assumed the optimal solution for it. Table 4 tabulates the

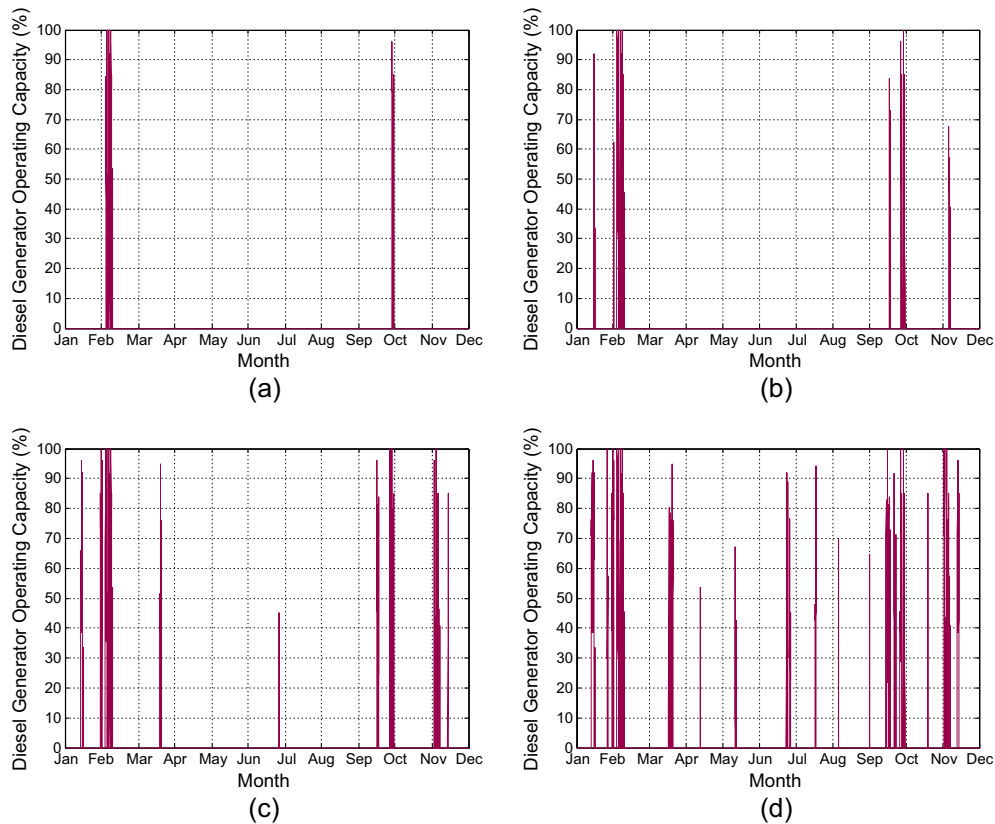


Fig. 22. Yearly diesel generator operation for scenario A, J, T and AE (three households).

**Table 4**  
Optimal sizing for PV alone, wind alone and PV–wind hybrid systems in Bishopton (three households).

System configuration	Cost of energy (£/kWh)	Percentage energy dumped	RESF	PRG	Number of wind turbines	Number of PV panels	Storage capacity (kWh)	Diesel gen capacity (kW)
PV–diesel system	1.55	36.5	0.701	1.24	0	110	60	3.03
Wind–diesel system	0.724	50.6	0.904	2.02	1	0	90	3.03
Wind–PV–diesel hybrid system	0.677	55.2	0.926	2.24	1	20	60	3.03

optimised system configuration results with three households being considered. Clearly, the wind–PV–diesel system gives the lowest cost of energy (£/kWh). On the contrary, PV–diesel system costs more than double of that wind–diesel and wind–PV–diesel system for total autonomy operation. This is partly due to the high utilisation of diesel generator, accounting for approximately 30% of total generation. This is also indicated by the low RESF.

Comparison of the wind–diesel system with the wind–PV–diesel system shows that an additional twenty solar panels allows a 33% reduction in the storage capacity. Note that this happens when there is a good complementarity between the wind and solar resources in the studied area. However, the downside is the about 10% increase of excess energy being generated. It would be better off if part of the excess energy is used for non-critical load like electric heater or refrigeration.

## 5. Conclusion & future work

This paper has given some insight and considerations that need to be taken into account when sizing storage capacity for hybrid wind–PV–diesel systems, both for daily and long term operation. The described methodology managed to take into consideration the peaks and troughs of a wind profile and solar irradiation. More

complex modelling and hardware testing are needed if more accurate estimation of batteries and diesel generator sizing is desired. In addition, more historical data on renewable energy sources (wind and solar) and load growth estimation throughout the hybrid system's life cycle can be taken into consideration. A life cycle analysis integrated into this work is recommended to portray the significance of fossil fuel emissions. In addition, the economics of demand side management and load shedding operations can be included in the future as they are not being considered here. Finally, the developed GUI can potentially be employed as a tool for project managers to size the hybrid system accordingly for various climates and load demand characteristics.

## Acknowledgements

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## Appendix A. Maintenance and cost calculations

Given that:

$$i = 0.03$$

$$d = 0.04$$

$$x = \left( \frac{1+i}{1+d} \right)$$

$$x = \left( \frac{1+0.03}{1+0.04} \right)$$

$$x = 0.9904$$

Considering  $n = 20$  years:

$$P_a = \left( \frac{1-x^n}{1-x} \right)$$

$$P_a = \left( \frac{1-0.9904^{20}}{1-0.9904} \right)$$

$$P_a = 18.277$$

$$P_{a1} = xP_a$$

$$P_{a1} = 0.9904 \times 18.277$$

$$P_{a1} = 18.1015$$

Present worth wind turbine maintenance cost for 20 years:

$$PW_{wind} = P_{a1}(C_o)$$

$$PW_{wind} = 18.1015 \times \text{£ } 500$$

$$PW_{wind} = \text{£ } 9050$$

Present worth solar PV panels maintenance cost for 20 years:

$$PW_{solar} = P_{a1}(C_o)$$

$$PW_{solar} = 18.1015 \times \text{£ } 100$$

$$PW_{solar} = \text{£ } 1810$$

Present worth batteries replacement for year 5, 10 and 15:

$$P_r = \left( \frac{1+i}{1+d} \right)^n$$

$$P_{r5} = \left( \frac{1+0.03}{1+0.04} \right)^5$$

$$P_{r5} = 0.9528$$

$$PW_{battery\ 5} = 0.9528 \times (\text{£ } 50)$$

$$PW_{battery\ 5} = \text{£ } 47.64$$

$$P_{r10} = \left( \frac{1+0.03}{1+0.04} \right)^{10}$$

$$P_{r10} = 0.9079$$

$$PW_{battery\ 10} = 0.9079 \times (\text{£ } 50)$$

$$PW_{battery\ 10} = \text{£ } 45.40$$

$$P_{r15} = \left( \frac{1+0.03}{1+0.04} \right)^{15}$$

$$P_{r15} = 0.8651$$

$$PW_{battery\ 15} = 0.8651 \times (\text{£ } 50)$$

$$PW_{battery\ 15} = \text{£ } 43.26$$

Present worth diesel genset replacement for year 7 and 14:

$$P_{r7} = \left( \frac{1+0.03}{1+0.04} \right)^7$$

$$P_{r7} = 0.9346$$

$$PW_{diesel\ 7} = 0.9346 \times (\text{£ } 300)$$

$$PW_{diesel\ 7} = \text{£ } 280.38$$

$$P_{r7} = \left( \frac{1+0.03}{1+0.04} \right)^{14}$$

$$P_{r7} = 0.8735$$

$$PW_{diesel\ 14} = 0.8735 \times (\text{£ } 300)$$

$$PW_{diesel\ 14} = \text{£ } 262.05$$

Present worth SMA inverters replacement for year 10:

$$P_{r10} = 0.9079$$

$$PW_{inverter\ 10} = 0.9079 \times (\text{£ } 9468)$$

$$PW_{inverter\ 10} = \text{£ } 8596$$

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